Summary: Fixed Target Experiments (E5)

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Snowmass 2001
20 Jul 01
Paul Reimer (ANL)

- Facilities
- CP violation
  - ε', $K^+ \to \pi^+\nu\nu$, $K^0 \to \pi^0\nu\nu$
- Spectroscopy
- Low-energy nucleon physics
- Structure Functions
  - Parton distributions
  - Spin structure functions
- Electroweak Standard Model
- μ-e conversion

[Neutrino physics and experiments at the front end of a neutrino factory belong to Group E1]

E5 working group participants

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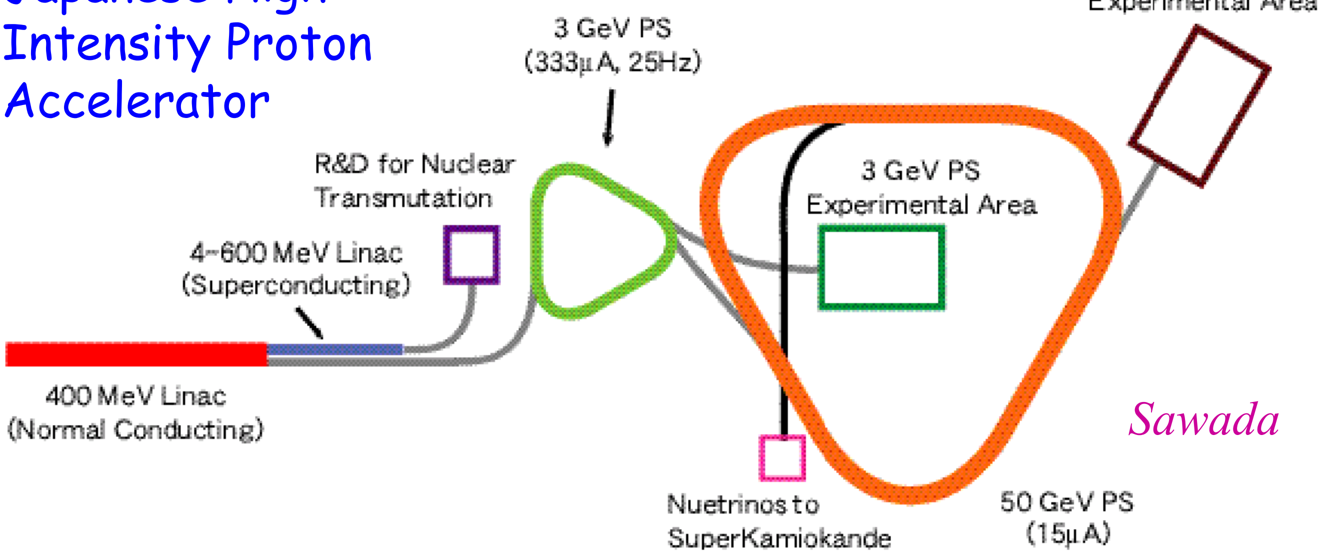
New (or improved) hadron facilities

Facility	Beam Energy	Intensity	Notes
Japanese High Intensity Proton Accelerator (JHF)	50 GeV protons	1 MW (5MW upgrade) 16 μA	Project is funded (phase 1) Completion in 2007 LOI's solicited soon
Brookhaven AGS	24 GeV protons	0.14 MW (1 MW upgrade 10^{14} at 2.5 Hz)	Available when RHIC runs Upgrade requires 1.2 GeV linac
Fermilab Main Injector	120 GeV protons	0.2 MW 3×10^{13} at 0.3 Hz	Low intensity beams ~2002 CKM in 2007

Low Energy AntiProtons

Commercial (medical) applications

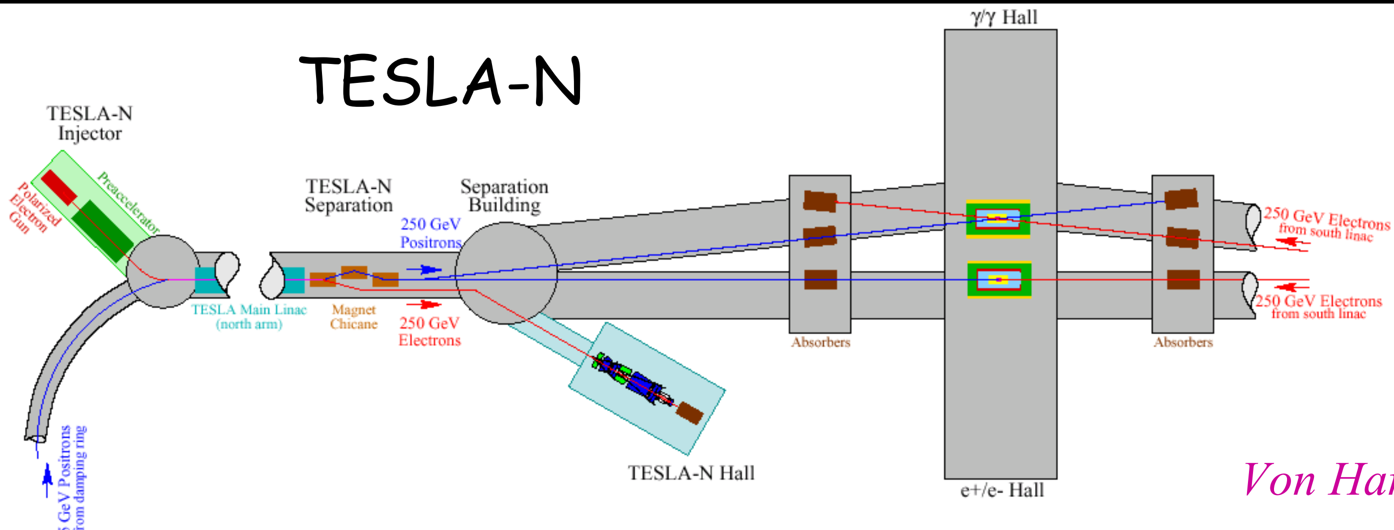
Japanese High Intensity Proton Accelerator



New (or improved) lepton and photon facilities

Facility	Beam	Intensity	Notes
Jefferson Lab	12 GeV polarized e^-	50 μA CW	New Hall D; 11 GeV Halls A, B, C Physics ~2008
SLAC End Station A	10-50 GeV polarized e^- polarized γ	10 μA 120 Hz	 Coherent bremsstrahlung
TESLA-N ELFE@DESY	250→500 GeV polarized e^- 20-30 GeV e^-	20 nA 5 Hz 30 μA CW	Populate missing RF buckets HERA ring used as stretcher
NLC	250-500 GeV polarized e^-	27 μA 120 Hz	Spent beam

TESLA-N



Von Harrach

CP violation

Sozzi, Blucher

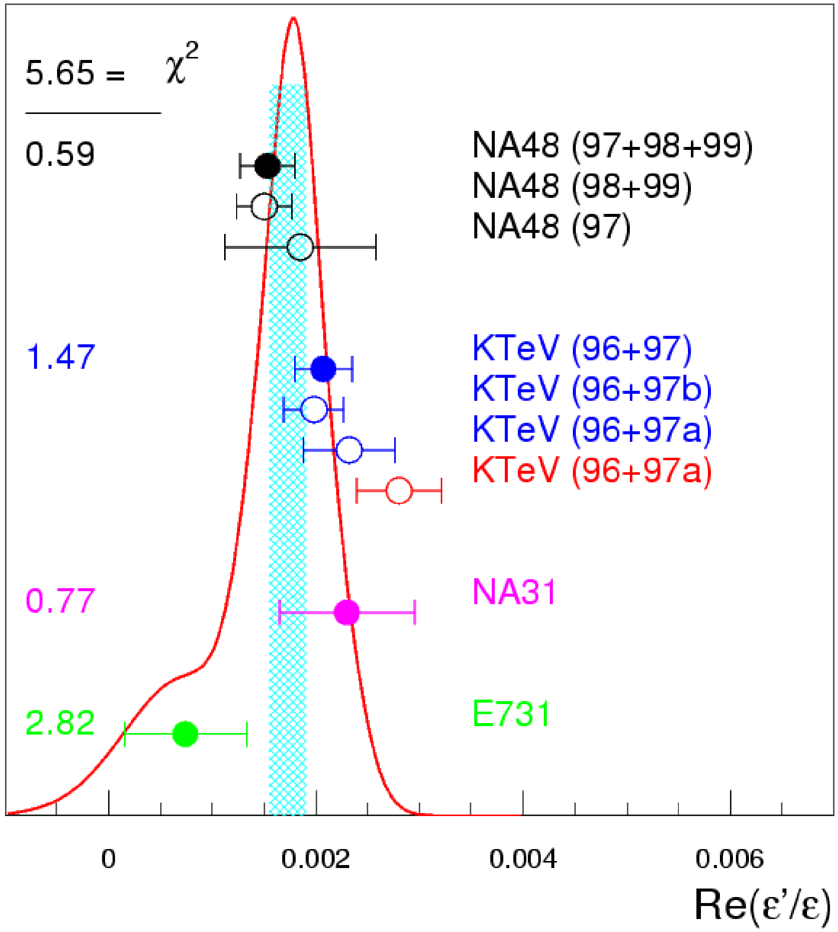
Fixed target experiments offer unique opportunities to address this physics.

ε'/ε results are now consistent; lattice calculations at relevant precision are at least 5 years away.

Direct CP violation is established, consistent with the CKM formalism of the SM.

Are there other sources of CP violation?

Almost any extension to the SM includes new possibilities for CP violation.



Naive average:

$$\mathrm{Re}(\epsilon'/\epsilon) = (17.3 \pm 1.8) \cdot 10^{-4}$$

with $\chi^2/\mathrm{ndf} = 5.65/4$

PDG scaled error $2.4 \cdot 10^{-4}$

CP violation (cont'd)

Ledovskoy

To search for new physics, the SM must be over-constrained and tested for consistency.

This requires control of experimental and theoretical errors. The only processes promising both are:

B decays: $B \to \psi K_s$, B_s mixing

K decays: $K_L \to \pi^o \nu\nu$, $K^+ \to \pi^+ \nu\nu$

$BR(K_L \to \pi^o \nu\nu) \propto |V_{cb}|^4 \eta^2 =$
$(3.1 \pm 1.3) \times 10^{-11}$

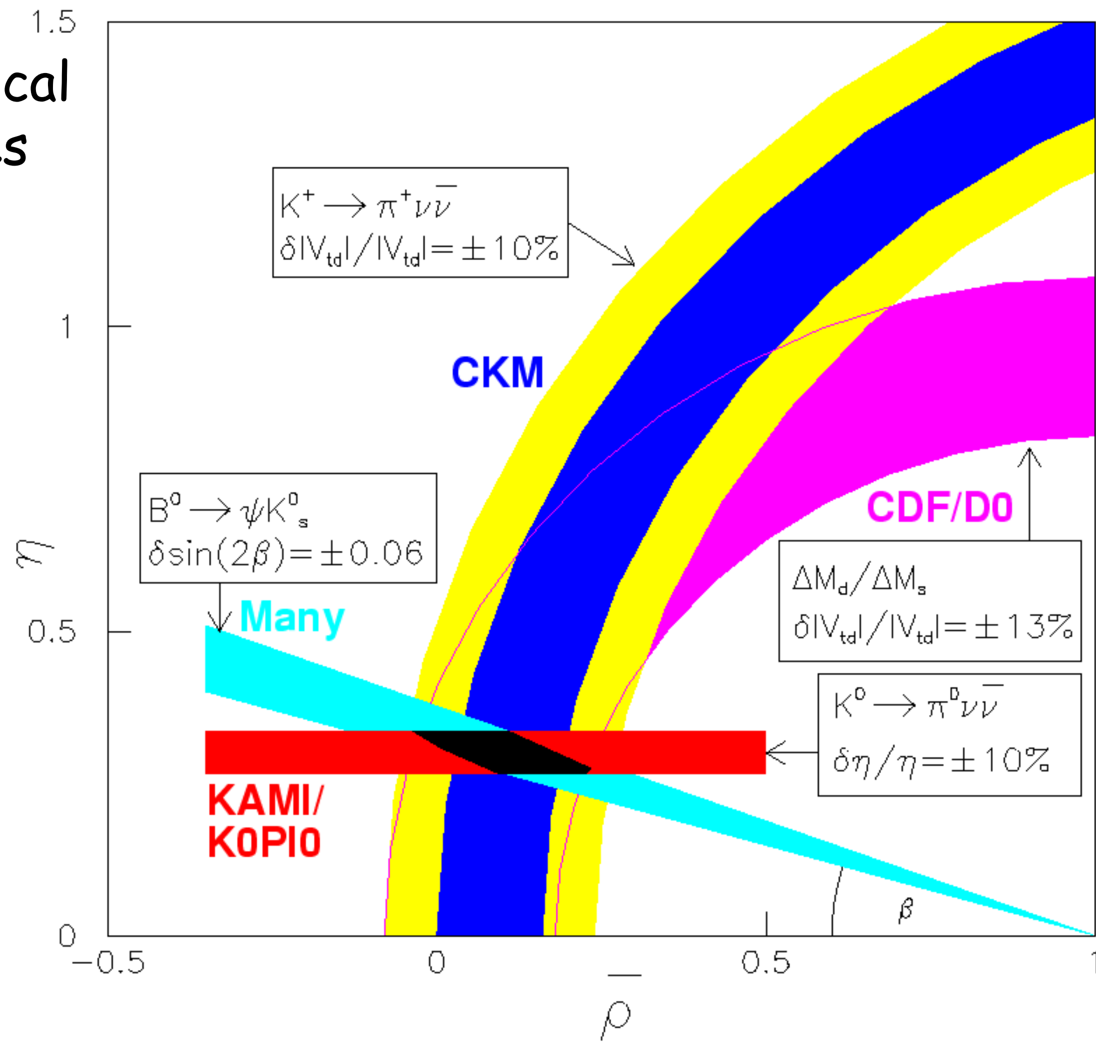
Theoretical error 1-2%

$BR(K^+ \to \pi^+ \nu\nu) \propto |V_{cb}|^4 |V_{td}|^2 =$
$(0.9 \pm 0.3) \times 10^{-10}$

Theoretical error ~5%

Experimental errors are dominated by V_{cb}, m_c and m_t.

Expected measurement precision for CKM parameters from K and B decays

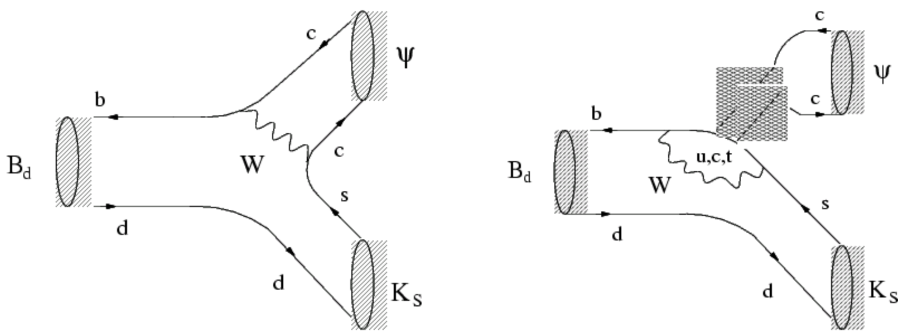


CP violation (cont'd)

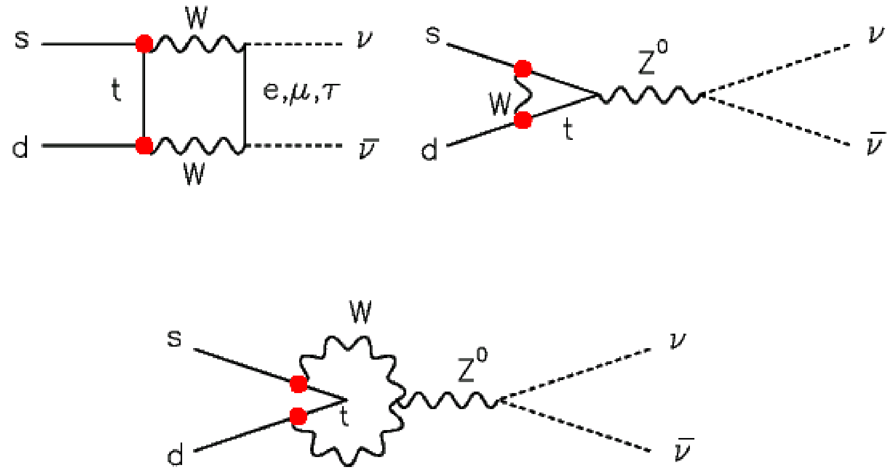
Together the two $K \to \pi\nu\nu$ measurements can determine $\sin(2\beta)$ without $|V_{cb}|$ uncertainty.

$K \to \pi\nu\nu$ and $B \to \psi K_s$ are distinctly different processes that could be impacted by new physics in different ways:

$B \to \psi K_s$ includes tree level processes:



$K_L \to \pi^0\nu\nu$ proceeds only through 2^{nd} order loop diagrams:



New physics could be manifested in different $\sin(2\beta)$ measurements from the K and B systems.

To fully explore the consistency of CP violation with the SM, all four well-controlled processes must be measured.

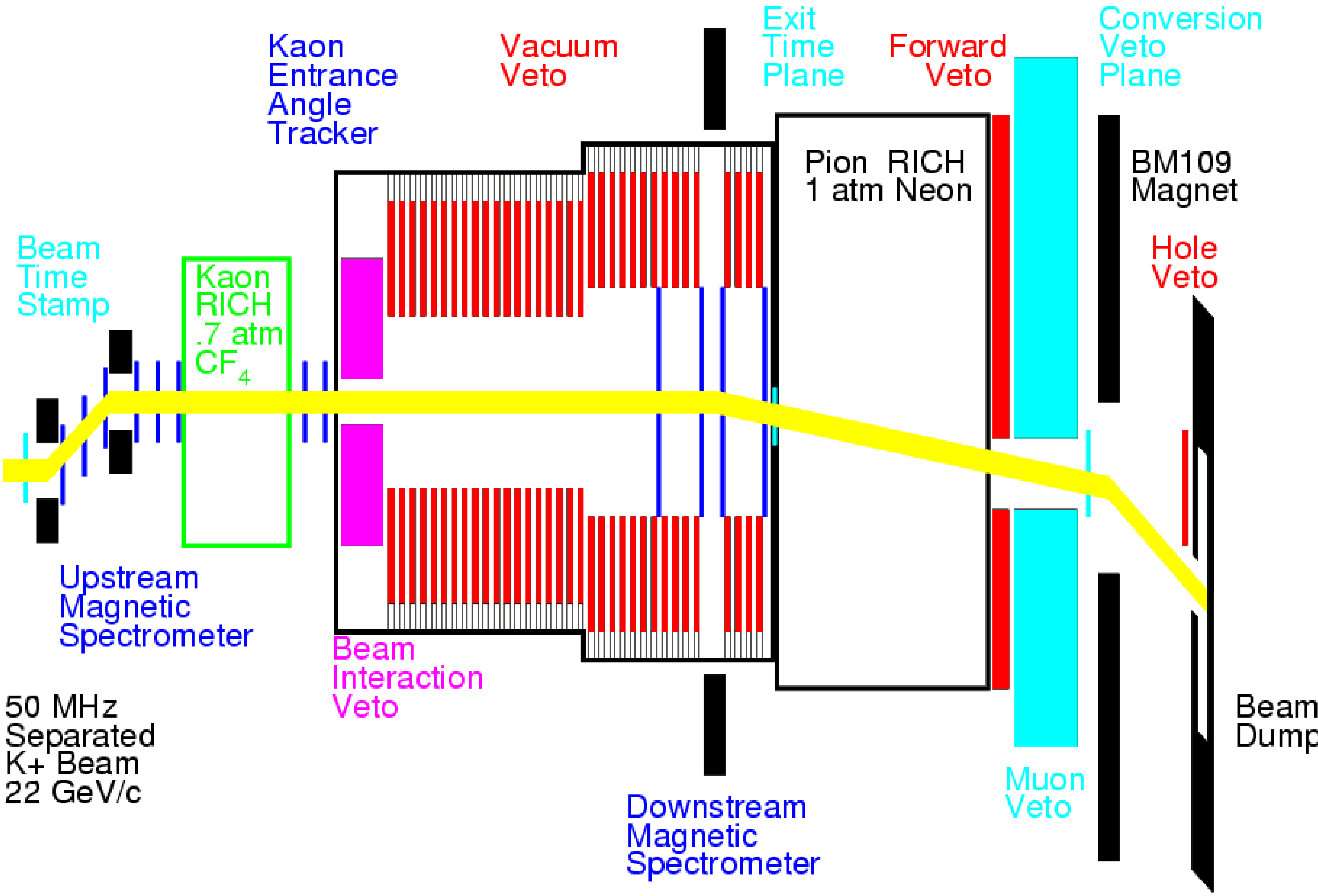
CP violation (cont'd): $K^+ \rightarrow \pi^+ \nu\nu$

Kushnirenko

BNL787:
Stopping experiment looking at K-μ-e decay chain -- 1 clean event.

BNL949:
Upgrade to 787: expects 5-10 events at SM level.

CKM:
Newly approved Fermilab experiment -- decays in flight with velocity spectrometer -- expect 100 events with 10% background.

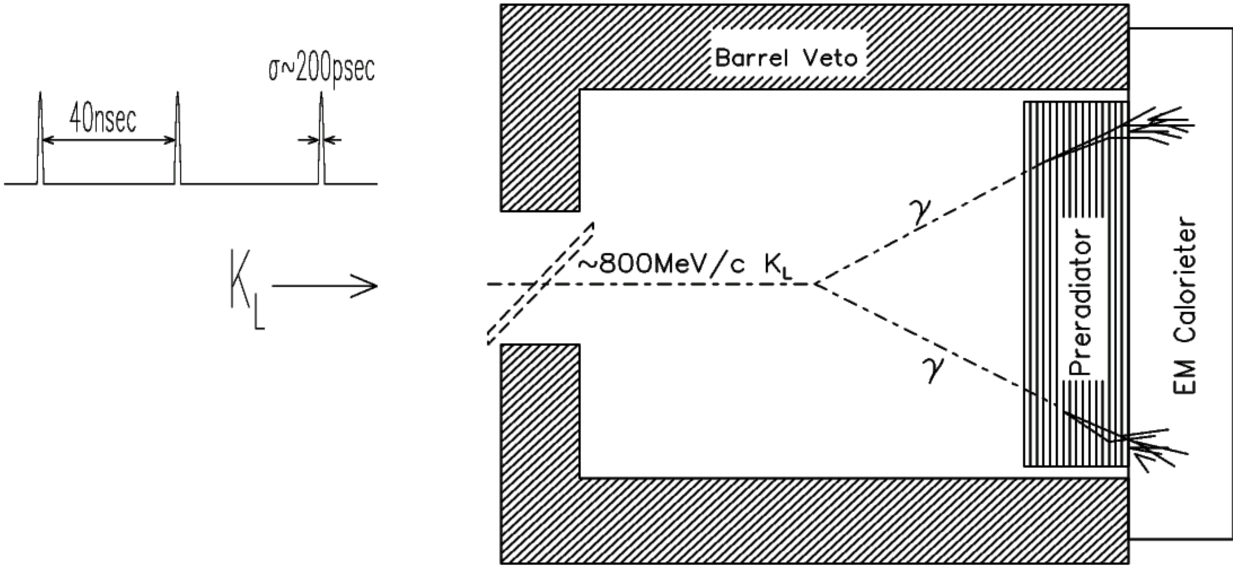


CKM detector

CP violation (cont'd): $K^0 \to \pi^0 \nu\nu$

Mildenberger

KOPIO: Low energy method using micro-bunched beam, kinematics from timing and photon pointing, hermetic photon veto. Experience from BNL787 measurement of $K^+ \to \pi^+ \nu\nu$ directly applicable. 40 events/yr at SM sensitivity with S/B of 2. Awaiting NSF construction funds.



KEK E791a: 10^{-10} SES measurement to run in 2003 -- engineering run for eventual JHF experiment to collect 1000 events. Backgrounds under evaluation.

Lim

KAMI: High energy method proposed at Fermilab. 90 events/yr at SM sensitivity with S/B of 4. Photon veto efficiency critical.

Ledovskoy

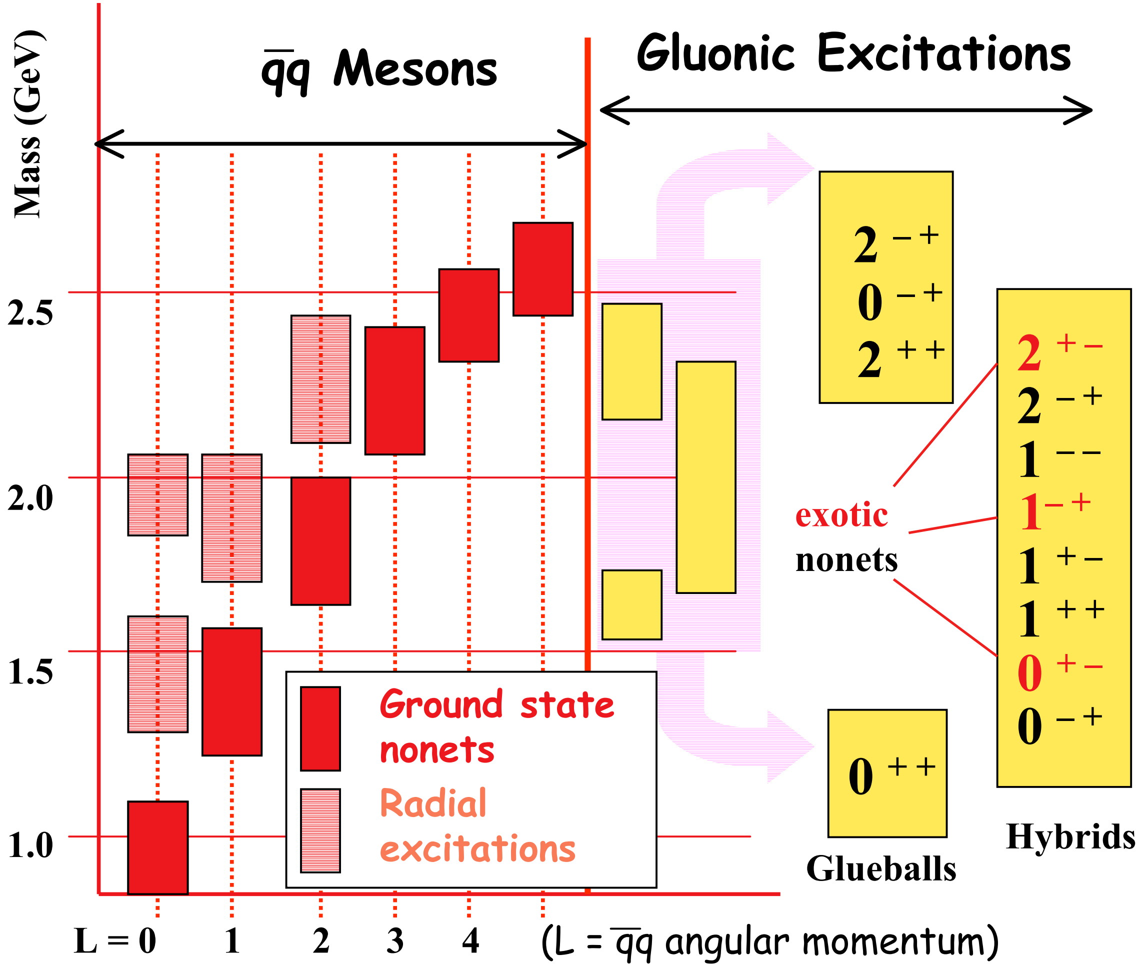
Spectroscopy

Hall D - Jefferson Lab

Focus on gluonic excitations leading to exotic QN. These are expected to be enhanced in photoproduction as opposed to pion beams owing to spin alignment of quarks in the probe.

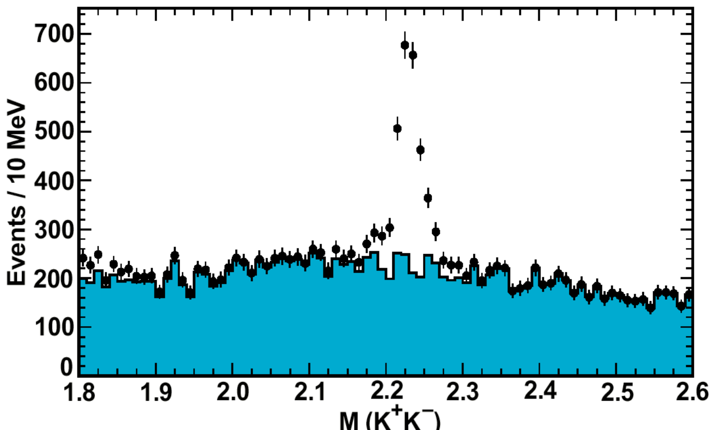
- Linear polarized photons for partial wave analysis
- Upgrade of CEBAF to 12 GeV

Dzierba



CLEO-C

Expected $f_J(2220)$



CLEO-C plans to make complementary measurements of:

Glueballs (non-exotic QN)

Charmed hybrids

Dytman

Particle physics with ultracold neutrons

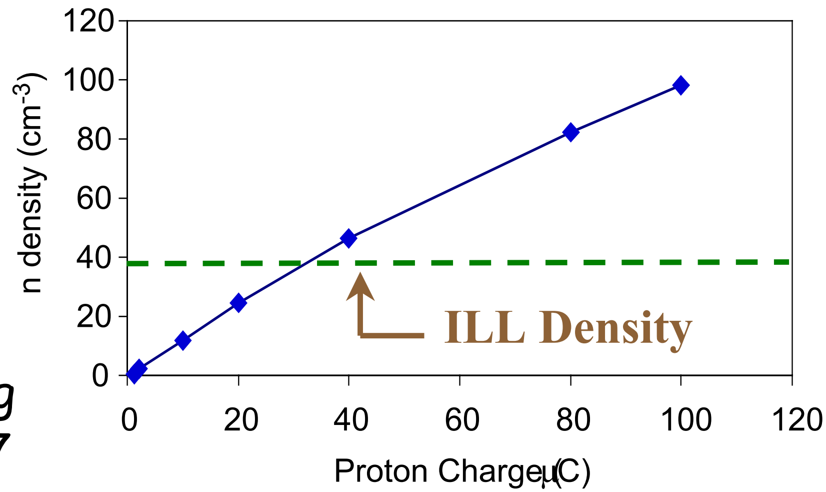
Bowles

Recent progress in superthermal UCN sources has demonstrated efficient production mechanisms

This has spawned a new generation of neutron experiments: LANSCE, NIST, ILL, PSI, KEK, …

The Spallation Neutron Source *Greene* should provide beamlines for the following generation of neutron experiments ~2007

World record UCN density at LANSCE



A permanent neutron electric dipole moment?

Cooper

- Sensitive probe of new sources of CP violation
- Current limit: ~10^{-25} e-cm
- Standard Model prediction: ~10^{-31}
- Many SUSY-GUT models predict values ranging from 10^{-27} to 10^{-25}
- New LANSCE experiment using Ultra-Cold Neutrons seeks to reach 10^{-28} sensitivity: feasibility experiments in progress; experiment launches ~2004

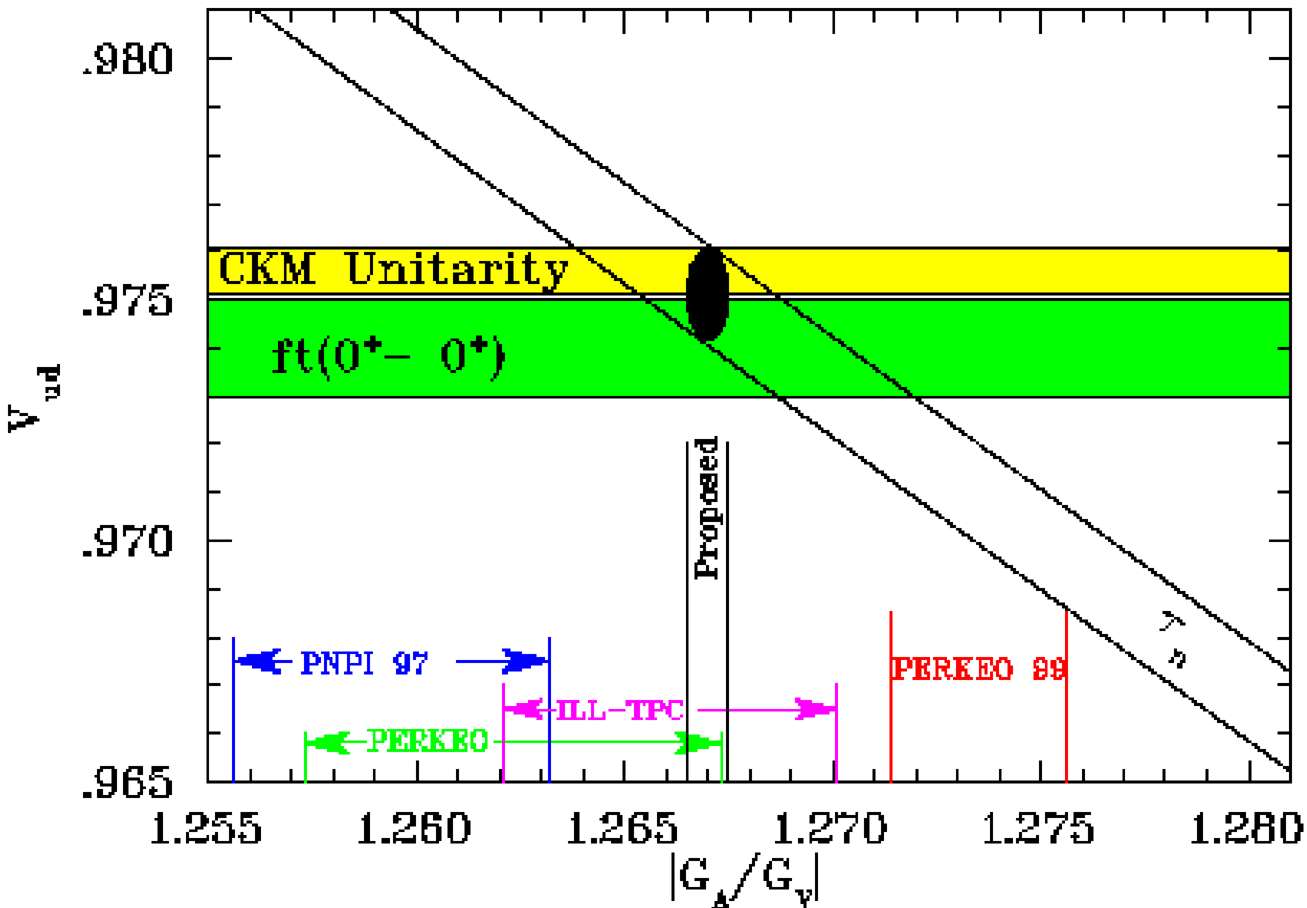
V_{ud} from neutron beta decay

Young

Unitarity test of the CKM matrix -- sensitive to new physics from SUSY and LR symmetric models:

$$(V_{ub})^2 + (V_{us})^2 + (V_{ud})^2 = 1$$

When current data including ft measurements of super-allowed nuclear beta decay are used, the error on V_{ud} dominates the unitarity test.



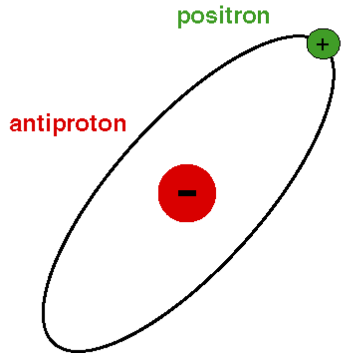
An alternative approach using UCN sources will allow more precise measurements of neutron lifetime and β-asymmetry.

UCNA collaboration at LANSCE:

- Proposed error on β-asymmetry ~ 0.3%
- Data taking planned ~2003

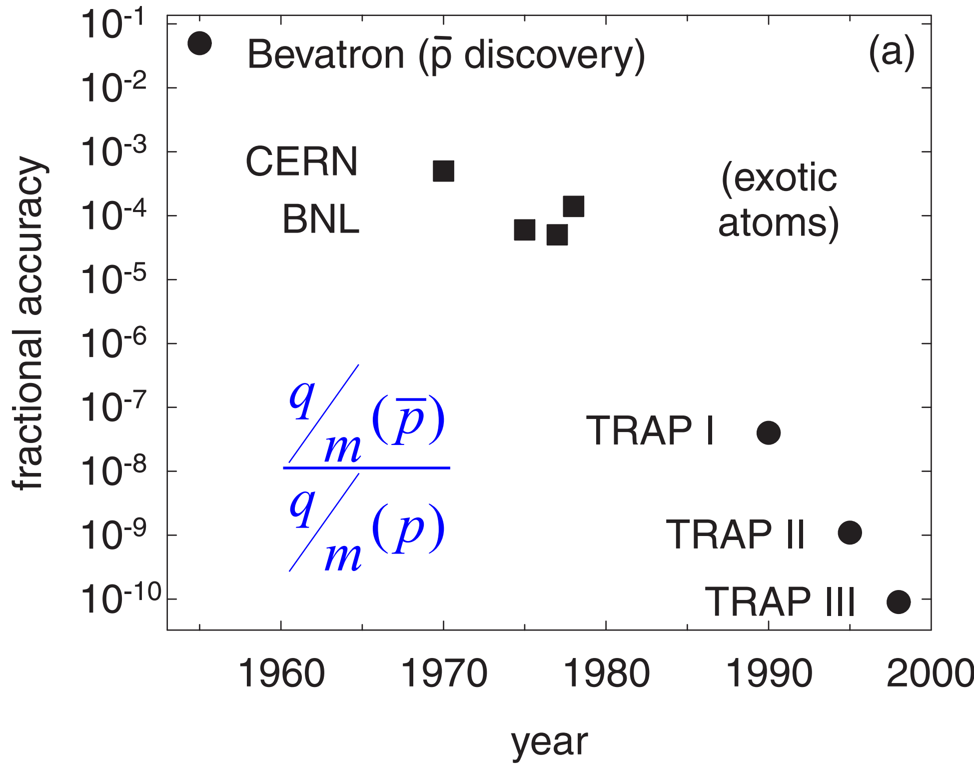
Precise CPT test using antihydrogen

Gabrielse



ATRAP collaboration goal: extend the proton – antiproton CPT test by comparing laser spectroscopy of hydrogen and anti-hydrogen

Best CPT test with baryons:



New facility: Antiproton Decelerator at CERN

Plan: make cold anti-hydrogen from cold antiprotons and positrons

Ultimate goal: improve lepton and baryon CPT tests to same level as $K\bar{K}$ system: ~10^{-18} accuracy

Unpolarized structure functions

What would we like to know?

Large-x proton structure is important.

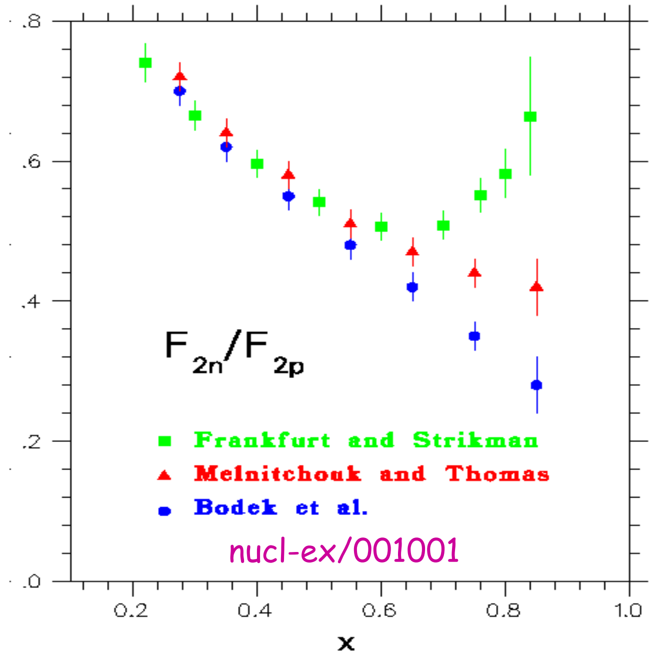
QCD evolution:

(large x, low Q^2) → (low x, high Q^2)

Intrinsic charm (bottom)? Need measurements near threshold.

Nuclear corrections ? (*Olness, Hoodbhoy, de Jager*)

Especially important at high x (JLab).



What happens to $\bar{d}/\bar{u}$ as x grows?

How is the nucleon's quark-antiquark sea generated?

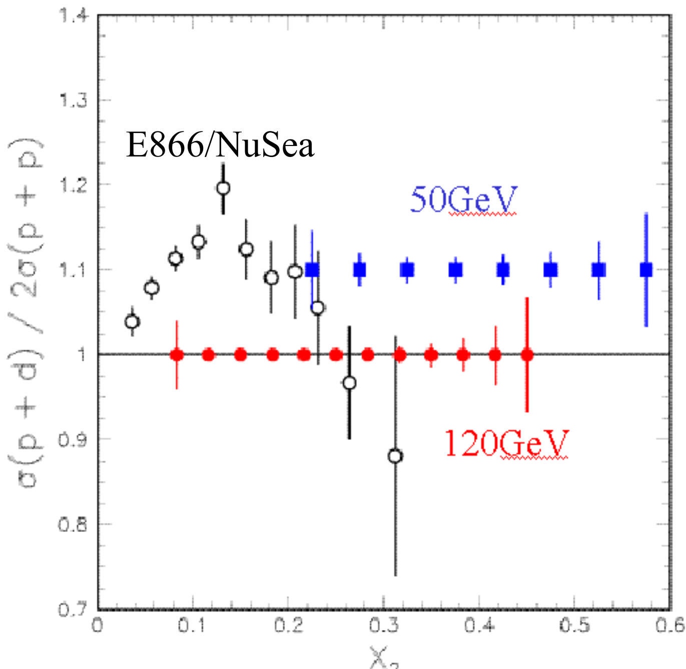
Gluon splitting ($g \to u\bar{u}$ and $g \to d\bar{d}$) cannot produce this asymmetry.

Fundamental to understanding of non-perturbative QCD.

Extract $\bar{d}/\bar{u}$ from **Drell-Yan** cross section ratio.

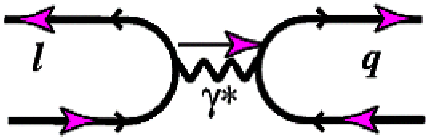
Fermilab P906 being considered.

JHF proposal also expected (*Sawada*).



Spin structure functions

What carries the spin S of the nucleon?

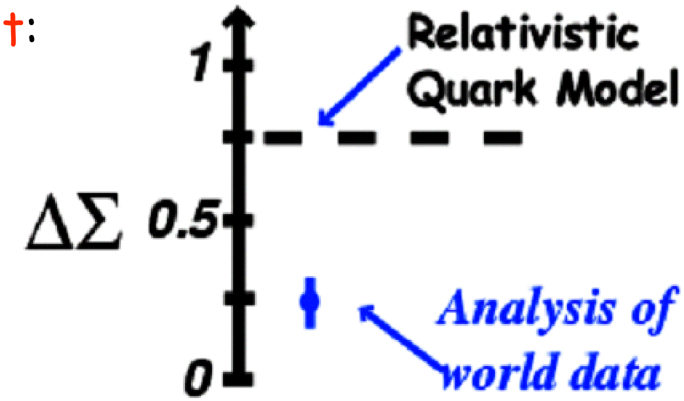


$$S = \frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quarks}} + \underbrace{\Delta G}_{\text{gluons}} + \underbrace{\Delta L}_{\text{angular momentum}}$$

Studied using spin-dependent deep-inelastic lepton-nucleon scattering.

Data on polarized ^{1}H, ^{2}H, and ^{3}He from CERN, DESY, and SLAC are well described by perturbative QCD.

These data establish a nuclear spin deficit:



The sea is implicated:
gluons are likely polarized.

The first direct measurements of gluon polarization will take place at DESY, RHIC, and SLAC over the next 5 years (*Kinney, Deshpande*).

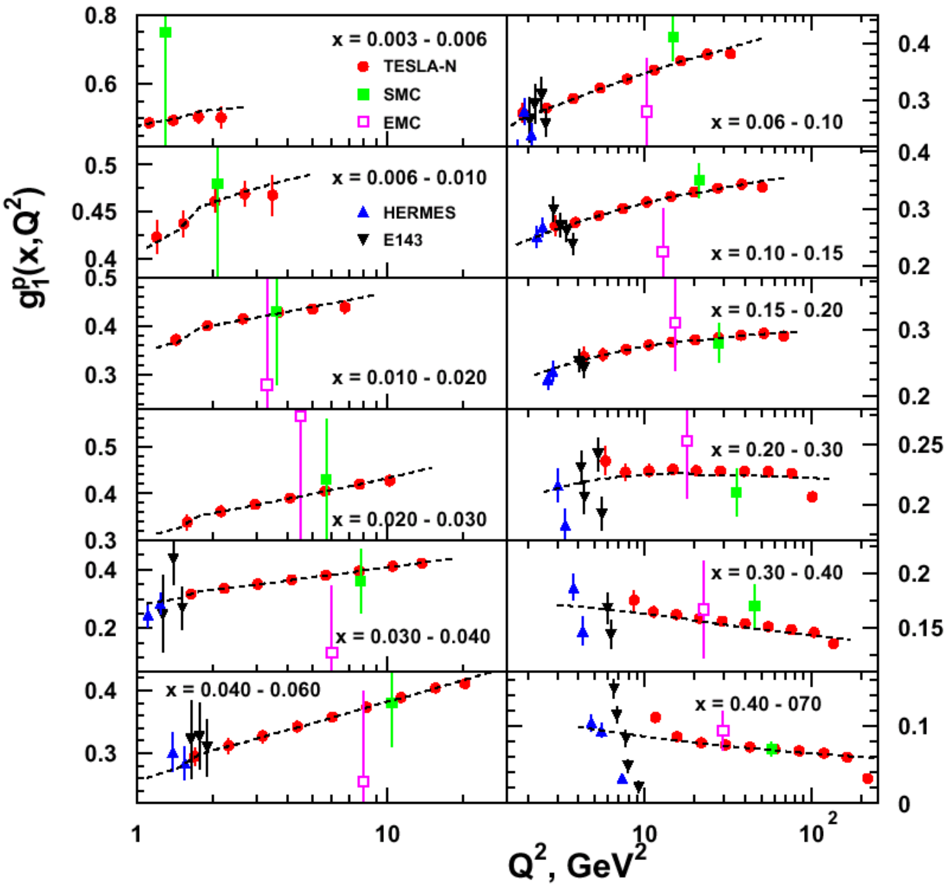
To cleanly establish gluon polarization and/or to discover a further spin deficit, precision measurements at new facilities would be required.

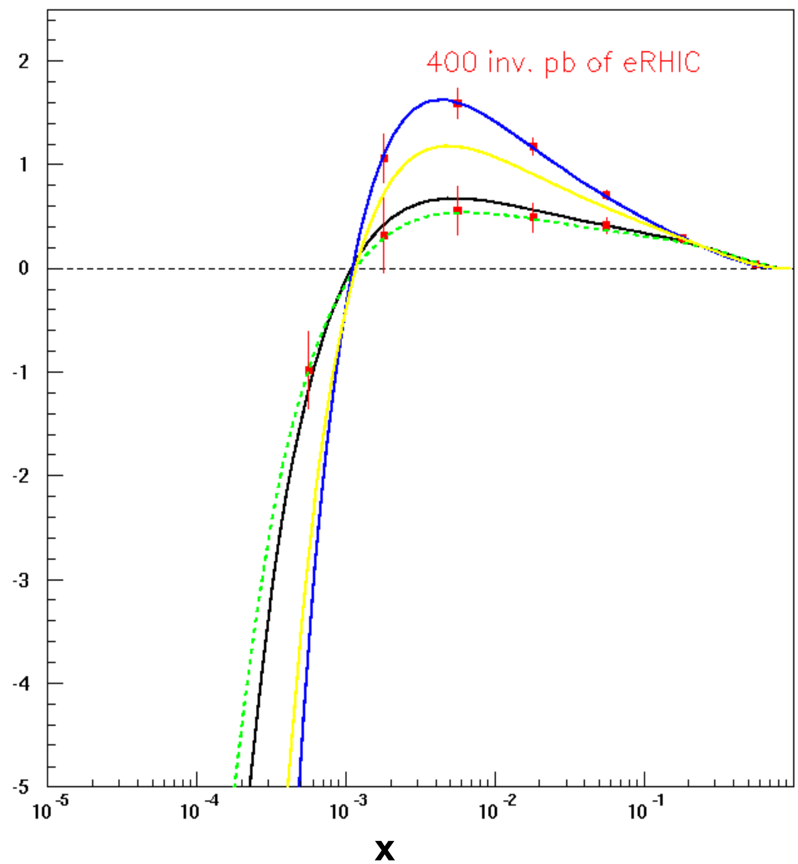
Proton spin structure function g_1^p

Ultra-precise measurements of spin dependent electron-proton DIS can be carried out either at a future linear collider or a polarized electron-hadron collider.

TESLA-N: 250 GeV e^- on fixed target

eRHIC: 3-12 GeV e^- on 50-250 GeV p



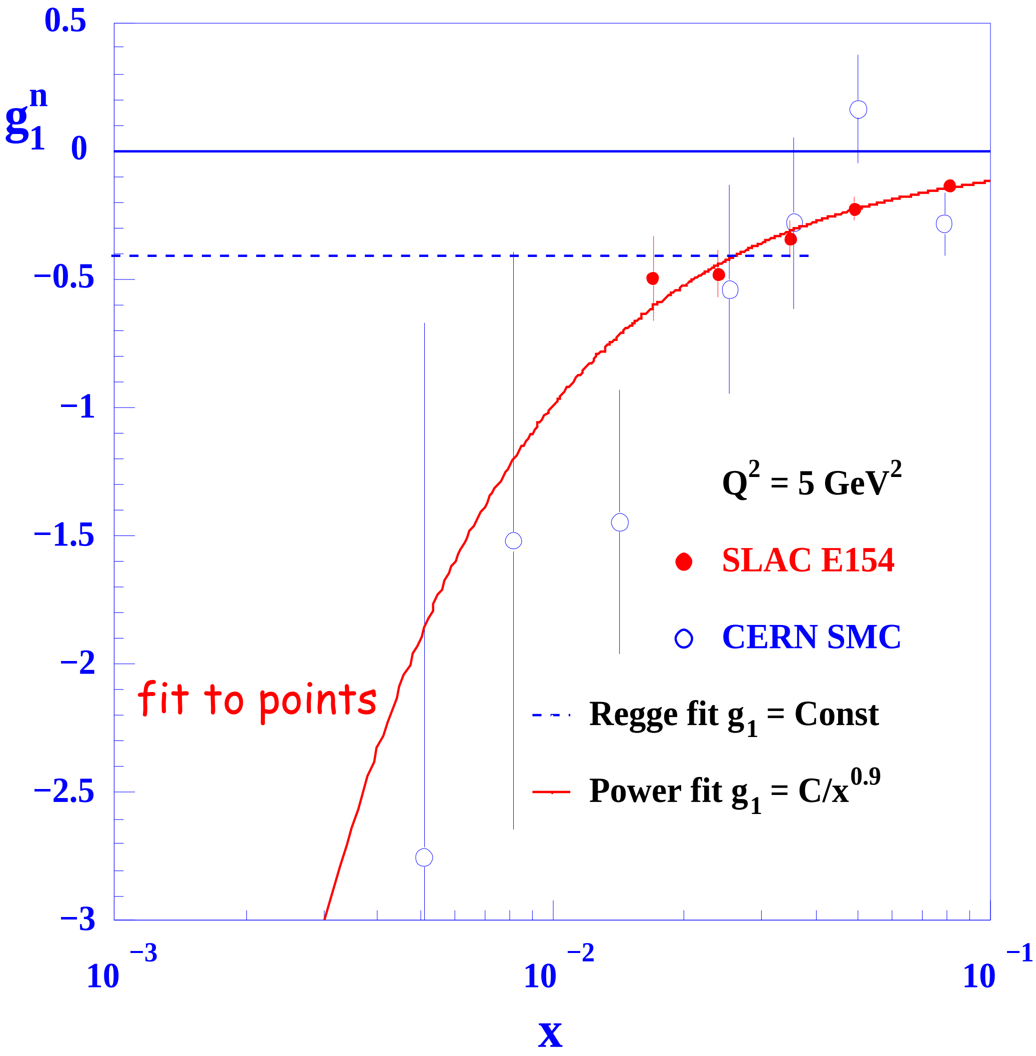


Von Harrach

Deshpande

Neutron spin structure function g_1^n

Ultra-precise measurements of spin dependent electron-neutron DIS require the full ("spent") beam current envisioned for a future linear collider.



Precision neutron measurements are feasible with a dense gaseous polarized ^{3}He target.

10^{14} e^-/sec are required.

g_1^n can be measured precisely down to $x \sim 10^{-3}$, establishing whether it is divergent.

Requirements on polarized beam properties are modest.

This is a clean experiment using the "spent" electron beam of a linear collider.

Kolomensky

Weak mixing angle from Møller scattering

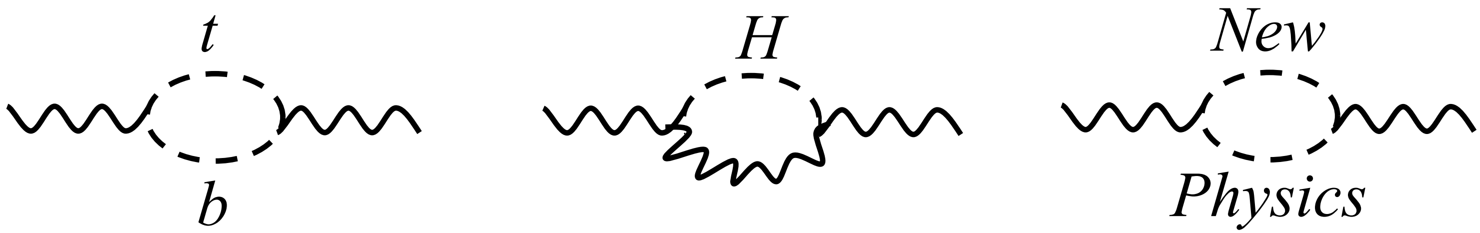
Marciano

Why?

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$ (natural relation at tree level)

$$\Delta\hat{r}(m_t, m_H, new) = 1 - \frac{2\sqrt{2}\pi\alpha}{G_\mu M_Z^2 \sin^2 2\theta_W (M_Z)_{\overline{MS}}}$$

loop corrections



$$\frac{\delta m_H}{m_H} \approx 10\% \text{ for } \delta \sin^2\theta_W \approx 0.00004$$ (world average ~0.0002)

Crucial consistency check if new scalars are discovered and identified

Comparison of $\sin^2\theta_W$ at different energy scales probes new physics, e.g. new gauge bosons, extra dimensions, compositeness,...

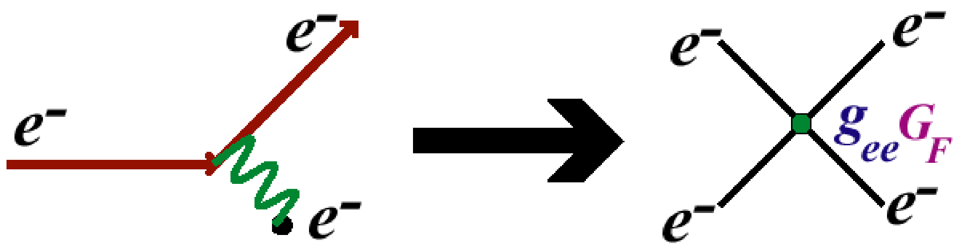
Weak mixing angle from Møller scattering (cont'd)

Souder

Several possibilities to achieve $\delta \sin^2 \theta_W < 0.00008$

- Giga-Z: 1 billion Z decays, with e⁻ polarization
- Polarized e⁻ e⁻ collisions at high energy with 250 fb⁻¹

- Fixed target parity violating e⁻ e⁻ scattering:



$$A_{LR} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = \frac{A_Z}{A_\gamma}$$

$$A_{LR} \propto (1 - 4\sin^2\theta_W)$$

50 GeV experiment underway at SLAC (E158): goal is $\delta \sin^2 \theta_W \approx 0.0007$

probes chirality violating compositeness scale to ~15 TeV

sensitive to Z′ from GUTS, extra dimensions ~ 0.8 - 2.5 TeV

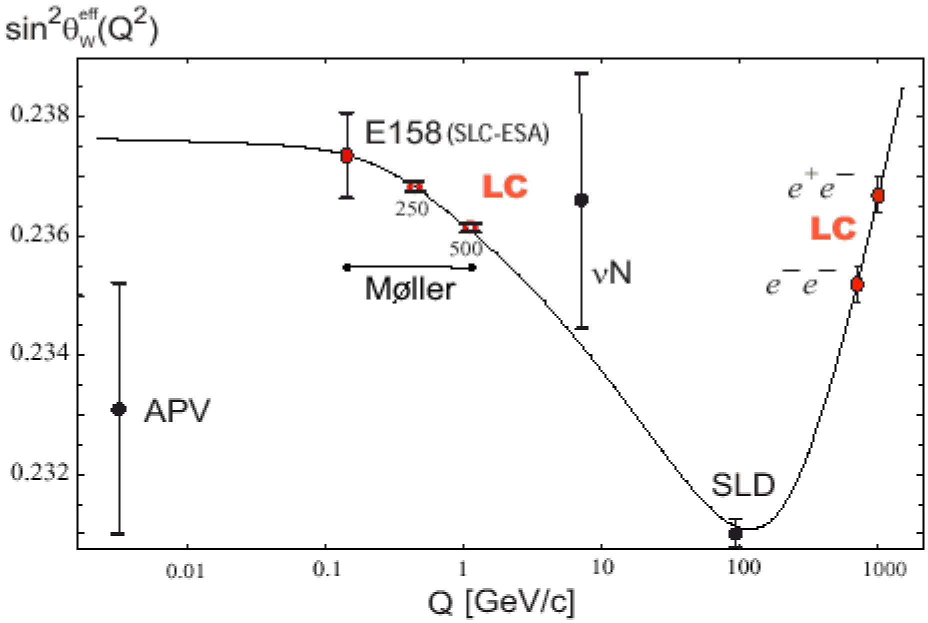
physics in 2002

Figure of merit rises with E_{beam}: 250-500 GeV experiment can potentially improve error by a factor of 10.

Weak mixing angle from Møller scattering (cont'd)

Possible experiment at a linear collider

	E158	LC
Energy (GeV)	48	250-500
Intensity/pulse	3×10^{11}	6×10^{11}
Pulse Rate (Hz)	120	120
P_e	75%	90%
Time (s)	5×10^6	2×10^7
A_{LR} (ppm)	0.18	1.8
δA_{LR} (ppm)	0.01	0.006
$\delta \sin^2(\theta_W)$	0.0007	0.00007



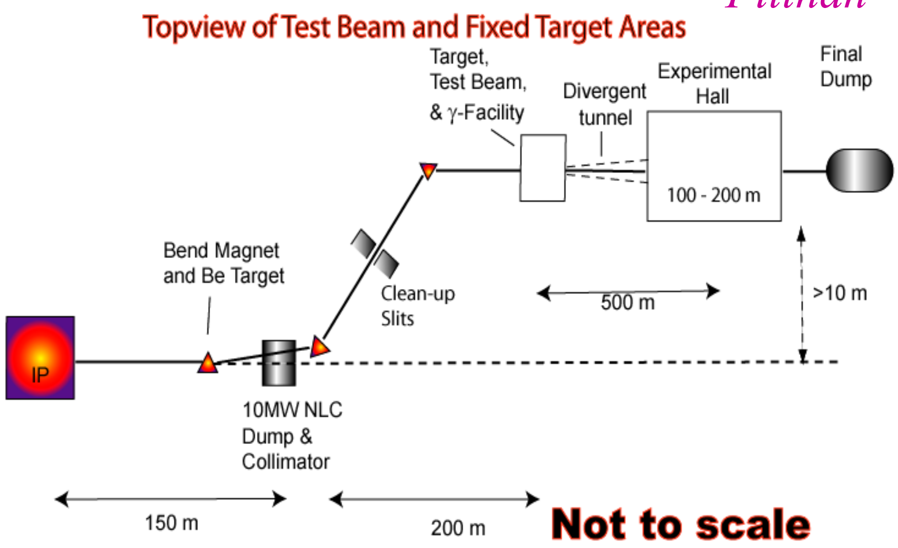
Compton Polarimetry
(dominant systematic error)

Woods

$$\delta P_e\,(\text{syst}) \approx 0.25\% \quad (\text{projected})$$
$$\approx 0.50\% \quad (\text{SLD})$$

$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} \approx \frac{1}{20}\frac{\delta P_e}{P_e} \Rightarrow \delta \sin^2\theta_W \approx 0.00003$$

Pitthan



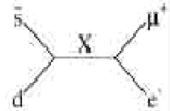
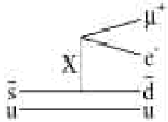
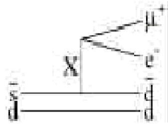
Molzon/Hebert

Searches for lepton flavor violation

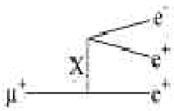
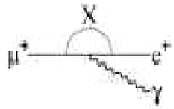
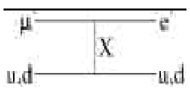
Experimental evidence supports near conservation of a family quantum number **G**.

These laws are accidental -- no known gauge symmetry protects lepton flavor.

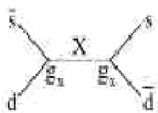
Essentially all extensions to the SM allow lepton flavor violation, which in the charged sector would be clear evidence for physics beyond the SM.

$\Delta G = 0$ or 2		Experimental Result (90% CL)	M or ΔM Limit
	BNL E871	$B(K_L^0 \to \mu^\pm e^\mp) < 4.7\times10^{-12}$	150 TeV/c^2
	BNL E865	$B(K^+ \to \pi^+ \mu^+ e^-) < 4\times10^{-11}$	31 TeV/c^2
	FNAL E799	$B(K_L^0 \to \pi^0 \mu^\pm e^\mp) < 3.2\times10^{-10}$	37 TeV/c^2

$\Delta G = 1$

		$B(\mu \to eee) < 1\times10^{-12}$	86 TeV/c^2
	MEGA	$B(\mu^+ \to e^+\gamma) < 1.2\times10^{-11}$ New PSI Experiment Goal $< 10^{-14}$	21 TeV/c^2
	SINDRUM2	$\dfrac{\Gamma(\mu^- A \to e^- A)}{\Gamma(\mu^- A \to \nu A')} < 6.1\times10^{-13}$ $< 4\times10^{-14}$ MECO Goal $< 2\times10^{-17}$ single event sensitivity	365 TeV/c^2

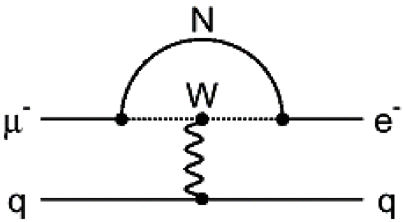
$\Delta G = \pm 2$

	$\Delta M_K < 3.5\times10^{-12}$ MeV/c^2	400 TeV/c^2

μ-e conversion

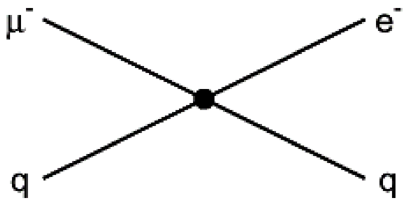
Marciano

Assuming MECO single event sensitivity of 2×10^{-17}



Heavy Leptons

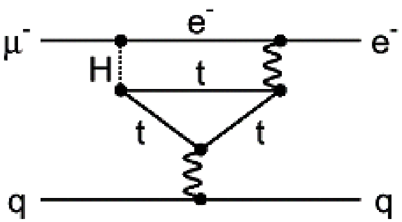
$$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$$



Compositeness

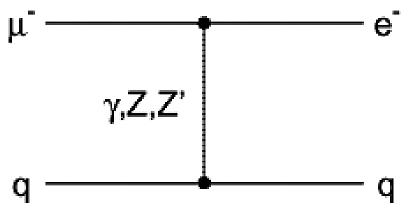
$$\Lambda_C = 3000 \text{ TeV}$$

Both $\mu N \to eN$ and $\mu \to e\gamma$ are sensitive to chirality violating amplitudes



Neutral Higgs

$$gH_{\mu e} = 10^{-4} \times gH_{\mu\mu}$$

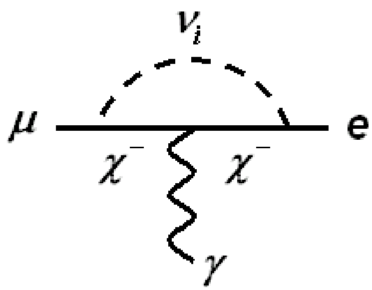


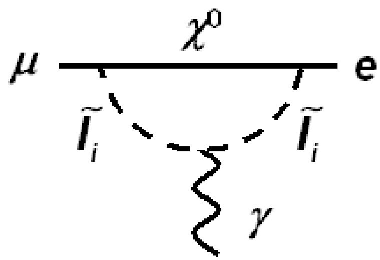
Z', Anomalous Z Couplings

$$M_{Z'} = 3000 \text{ TeV/c}^2$$

$$B(Z \to \mu e) < 10^{-17}$$

For example in SUSY models:





$\mu N \to eN$ is uniquely sensitive to new chirality conserving amplitudes

If muon g-2 result holds ⇒ might expect of order 100 events in MECO, depending upon details of masses and mixing

μ-e conversion at BNL AGS: MECO

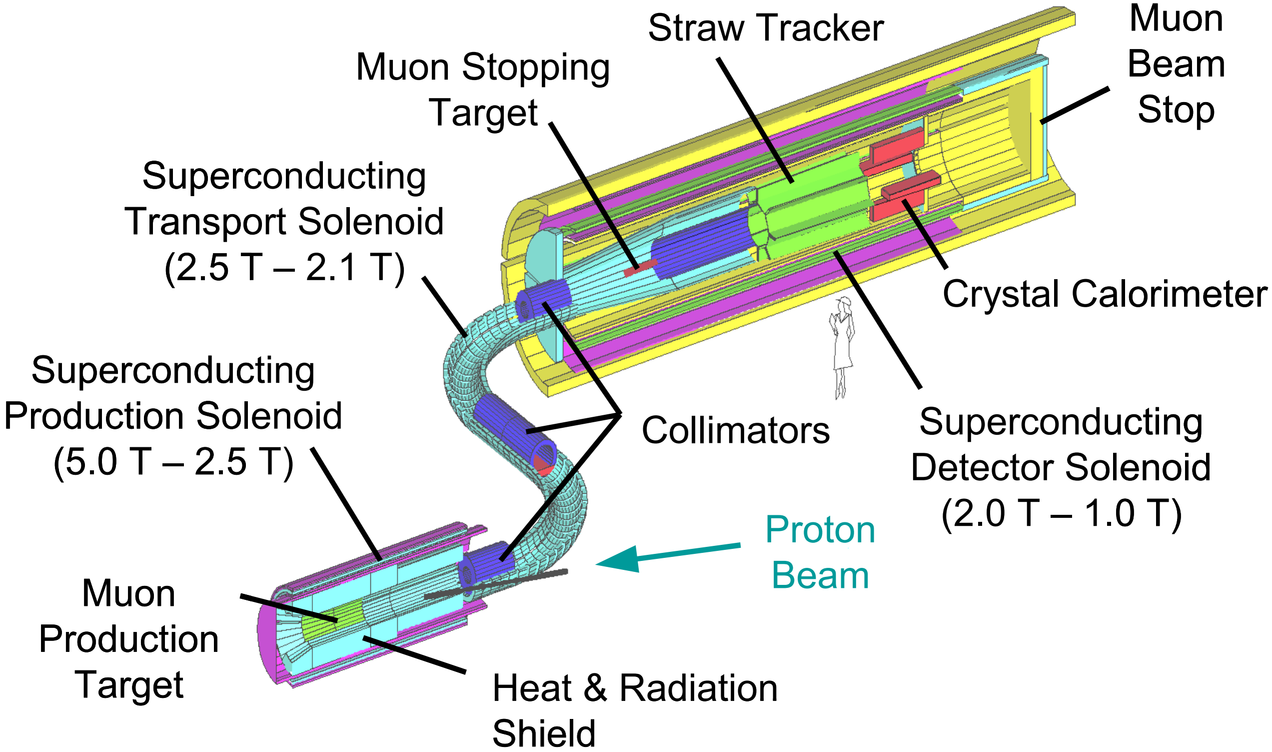
Molzon/Hebert

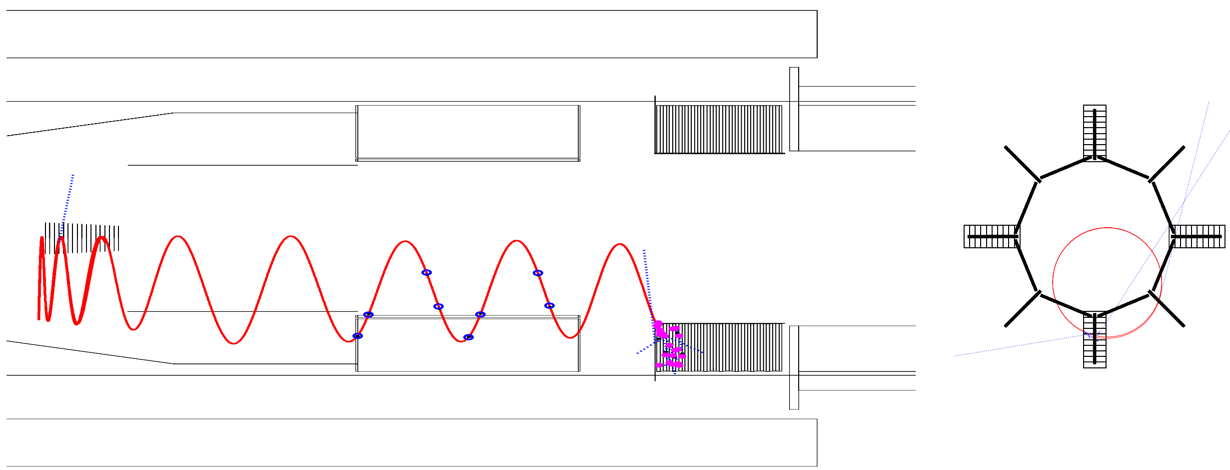
Essential ingredients:

Higher (×1000) muon flux (idea from MELC at MMF): high Z target; capture π's in graded solenoidal field; transport μ's in curved solenoid.

Pulsed beam (nsecs every μsec) to eliminate prompt backgrounds, as at PSI.

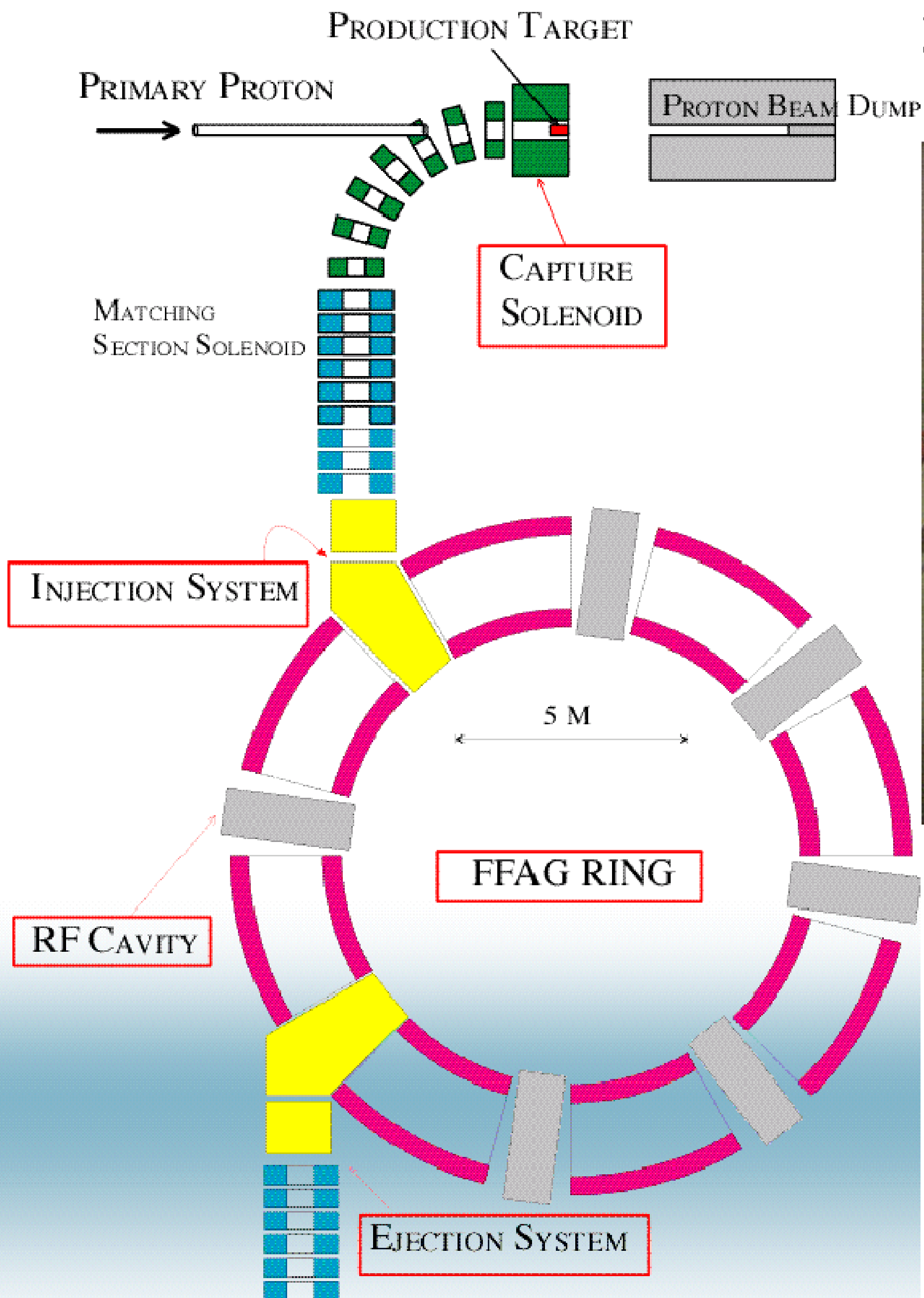
Detector with improved resolution, background rejection, and rate tolerance: immersed in graded solenoidal field; ~axially symmetric, high resolution elements.



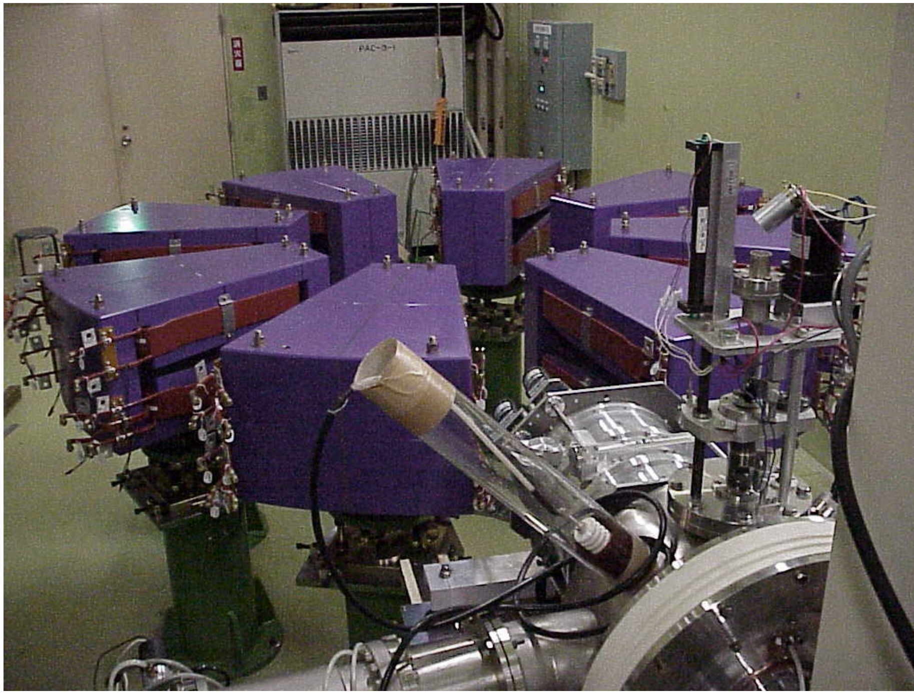


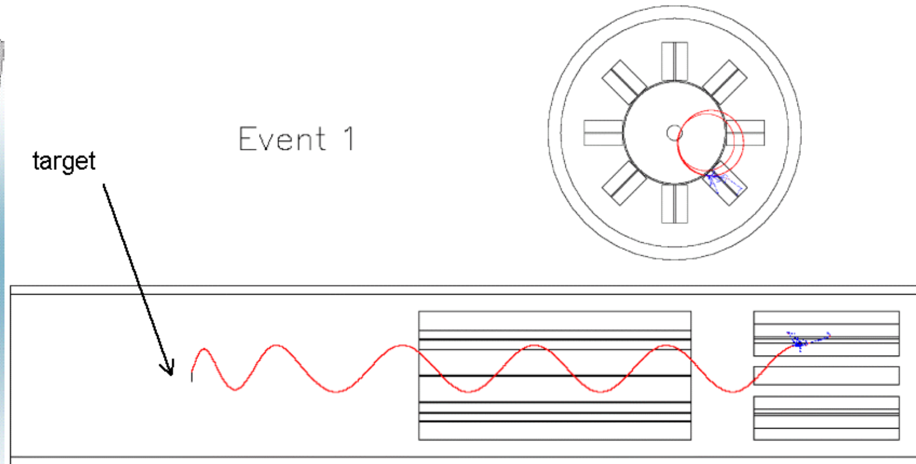
Ideas for μ-e conversion at JHF

Kuno



JHF muon beam would use an FFAG ring (model below) to coalesce momenta.





Ideas for μ-e conversion at JHF (cont'd)

Yoshimura

MECO is a fully designed, simulated, and costed proposal awaiting NSF construction funds.

PRISM (μ-e conversion at JHF) is exploring a conceptual design, and is not yet part of the Phase 1-2 JHF program.

PRISM hopes to extend MECO's single-event-sensitivity by a factor 50-100 to ~$2\text{-}4 \times 10^{-19}$, based on two key elements:

1. Higher proton current at JHF, leading to a 10-40x increase in muon rate.

2. Muon Δp vs. Δt phase rotation using a FFAG ring, collapsing the muon momentum spread, with two major benefits:
   - Muons stop in a thinner target, allowing improved electron energy resolution.
   - Pion, proton, and neutral backgrounds are suppressed.

But the FFAG's 1 kHz $\rightarrow$ 100 kHz(?) pulse rate isn't ideally matched to the muon lifetime: faster detectors would be required.

Closing thoughts

Fixed target experimentation remains vigorous and important.

In certain cases, the information that is sought…

…wouldn't readily be obtained if other techniques were used, and

…could change our thinking about elementary physics.

This workshop has reminded us of some examples:

Well-controlled tests of the SM CP formalism in K decay

Ultraprecise determination of the weak mixing angle and its evolution

Lepton flavor violation tests at PeV scales in the charged sector

As new facilities are planned, we should identify any unique opportunities that would be presented by fixed target experiments there, and, where it is practical, we should sieze those opportunities early on.